PI CONTROLLER BASED POWER CONDITIONING SYSTEM FOR SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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PI CONTROLLER BASED POWER CONDITIONING SYSTEM FOR SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

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By

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Dedicated to my friends.

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CERTIFICATE

This is to certify that the Thesis Report entitled "**PI CONTROLLER BASED POWER CONDITIONING SYSTEM FOR SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM",** submitted by Mr. NIKHIL CHANDRA DEVARASETTI bearing roll no. 213EE4321 in partial fulfillment of the requirements for the award of Master of Technology in Electrical Engineering with specialization in "Power Electronics and Drives" during session 2013-2015 at National Institute of Technology, Rourkela is an authentic work carried out by him under our supervision and guidance.

To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

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ABSTRACT

A Superconducting Magnetic Energy Storage System (SMES) works on the principle of superconductivity, which is a phenomenon of occurring exactly zero resistance in certain materials when they are cooled below a certain temperature. The power conditioning system (PCS) of SMES consists of a bidirectional voltage source converter (VSC), a bidirectional chopper and a superconducting coil, which I designed mainly for the compensation of non-linear and pulsating loads. In this paper the PCS of SMES is designed to work both as a shunt active power filter and power conditioner at the same time. Two Hysteresis band controllers have been used to generate the pulses for the two bidirectional converters so as to attain the sinusoidal input source current at any load condition and to maintain the charge discharge cycle of SMES. DC link voltage is kept constant by DC/DC Bidirectional Converter and source current is controlled by Voltage Source Converter (VSC). At light loaded condition the superconducting coil will be in the charging mode and heavy loaded condition the superconducting coil discharges the stored energy in order to compensate the load changes, which is done with the help of a PI controller. The total harmonic distortion (THD) of the charging and discharging mode is well below 5% of the fundamental component. Simulation has been done in **MATLAB/Simulink** and results presented demonstrating the reliability of the power conditioning system.

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CHAPTER-I

1. **Introduction**
2. **Literature Survey**
3. **Research Actuation**
4. **Objective**
5. **Thesis Composition**

1.1 Introduction

Superconductivity is a phenomenon of exactly zero resistance in certain materials when they are cooled below a certain temperature. SMES (Superconducting Magnetic Energy Storage System) is a large superconducting coil that can store energy indefinitely in the form of magnetic field generated by the dc current flowing through it. Some main applications were energy storage, system stability enhancement, diurnal load leveling and voltage stability (Transient and dynamic), static VAR compensation, current harmonics mitigation. Load demand usually very high from industries and commercials, where the load demand varies from time to time. So it is very essential to maintain the system stability by compensating the extra load demand if there is any sudden demand. At peak load conditions the voltage at the terminal end keeps falling and at light load condition there is a possibility of Ferranti effect, which are not desirable to the power system. So, load levelling plays a major role in satisfying or compensating the demand from the industries or commercials. This also helps industries from paying penalty for violating the maximum power demands and also power factor violations. So in order to ensure this the large batteries or SMES are used. But maintaining the large batteries is a very costly affair. So, SMES systems have been used, which is reliable and low cost compensator [1].

The PCS of SMES comprises of a bi-directional VSC and a bidirectional chopper and a superconducting coil. Choice of a current source would be obvious as the coil acts as a current source, but at higher power ratings the fluctuations in SMES coil current and voltage would be very high and is impractical to use CSC [2]. Therefore, the VSC converter will be the perfect choice but an extra bidirectional chopper has to be included into it between the VSC and the coil. The two converters are decoupled with a dc-link capacitor. The VSC converter will first interface the capacitor with the AC power supply. And it is controlled to get the source current in phase with the source voltage at any load. The DC/DC chopper interfaces the dc-link capacitor with the SMES coil, which controls the charge discharge cycle of SMES and also by ensuring the capacitor voltage constant, which makes the direct exchange of power between grid and coil.

Due to a lot of advantages and simplicity in designing the hysteresis band controllers, they are used to generate pulses for the two converters [5], [6]. The VSC controls the source current (I_s) to act as an active power filter. The DC/DC chopper is used to control the charge-discharge cycle and the capacitor keeps the voltage across the chopper constant. The hysteresis controller binds the controlled variable with in the selected limit. Switching pulses are generated accordingly. The actual energy and the reference energy were being compared and given to the PI controller and the output is being passed through a saturation block, which sets the maximum current limit of the coil, and subsequently a reference current generated is compared with the actual to generate the pulses for the VSC. The other hysteresis band controller is used to generate pulses for thee DC/DC bi-directional chopper by comparing the actual and reference voltages. The reference energy of the coil is found out by using the maximum current that is set to be flowing in the superconducting coil and the reference capacitor voltage depends on the line to line supply voltage of the source. A non-linear diode rectifier is taken as a load. The pulsated character of SMES coil current shows us that there is the AC current loss in the coil which are considered while designing SMES refrigeration system [3].

1.2 Literature Survey

The research and innovations has been seen in the field of SMES for the last forty years. But the serious research work is only started in the early 70's by Wisconsin University and the department of Energy at Los Alamos national laboratory [11]. EPRI has funded the study to know its feasibility and applicability practically since the early 80's. To dampen the power oscillations on Pacific Inertie, both the department of energy and Bonneville Power Administration conducted experiments on a 30MJ SMES on Western US Power System in 1983 [12]. In the mid 80's the department of defense believed the SMES technology would become a potential investment and a useful power supply to the Ground Based Free Electron Laser (GBFEL) [13].

A 22 MWhr - 400 MW SMES ETM had been taken to design and test by the DNA. The two main objectives of ETM is to describe the applicability when there are load fluctuations and to show how it can be a reliable power supply when there is a sudden change in load by maintaining the system stability. And the other objective is to explain how SMES is compatible as a power supply to ground based defense systems [2]. The project basically consists of two groups of SC coils with 50A and 61.2H each and the PCS consists of 4 modules with a 24-pulse VSC, a two-quadrant chopper and a SC coil in each module. And each 24-pulse VSC with 4 3-Ø 6 pulse VSC's having a switching device GTO with an anti-parallel diode. And also to generate a 24 pulse waveform 4 $\mathrm{Y}-\Delta$ transformers were connected in parallel. There they controlled $P_{out}\ and\ Q_{out}$ to generate pulses and by a differential real power command the SMES coil currents were balanced. In the early stages they used CSC to compensate the increased load in power conditioning system (PCS) of SMES as the SMES is current controlled device. The storing and supplying of energy in SMES can be controlled directly by switching sequence of CSC. In this model the ac supply is connected to one side of CSC and the SC coil on the other side. The exchange of P and Q becomes very fast and independent because of inherent characteristic of SMES.

In the late 90's the PCS had been developed to compensate constantly changing which are non-linear in nature [14]. IGBT's were used in the voltage source converters as switches and PI controllers were used to compare and regulate the SMES coil energy, dc-link $V_{capacitor}$ and the also I_{source} in this paper. The most important objective was to make I_{source} in phase with V_{source} even when there is a change in load which are non-linear in nature. Gains were being found out by studying the control loops.

The developed power conditioning systems till 2003 used to control the SMES in voltage regulating mode, which is said to be charging in constant voltage and the duration of charging is also very high. Therefore a controller had been proposed which helps SMES to charge very smoothly with a constant current regulation mode which also makes the SMES coil to be ready as instantly as possible to discharge as and when needed [15]. The charging was done by constant current regulating mode and the discharging was done by constant voltage regulating mode in order to compensate the increased the loads instantly. The bidirectional operation is done with a SPDT switch in PCS in order to attain this control operation. The voltage source converter used is IGBT based and I_{source} control is obtained by PI controller.

In the early stages PI regulators had been used to regulate I_{source} which had shown a poor performance when parameter changes occurred. So the researches introduced hysteresis controller in order to control the I_{source} and also a fuzzy logic controllers in place of PI regulators.

Many other applications of SMES were demonstrated other than load and harmonic compensation and in the papers [31] [32] [33] [34] [35]. Some main appl., of SMES are $V_{stability}$, power regulation in the tie-line, frequency regulation during load changes, SRD, spinning reserve etc.

1.3 Research Actuation

In the energy storing applications the BESS and the hydroelectric pumped storage systems are as useful as SMES systems. The main liability in the BESS is that its life cycle is limited and easily prone many environmental misfortunes. Some other liabilities of pumped storage hydroelectric systems are the big any heavy unit size, the provincial and environmental problems [4]. SMES can store the energy for infinite periods and even supply the energy for infinite amount of time if needed as its resistance is theoretically zero and therefore zero time lag. This characteristic usually makes SMES to supply energy practically within milliseconds. Load compensation has got prominence in modern power system when the load demand is high and rescue the system from possible collapse.

Because of the leading technologies, the harmonic pollution is caused by all the power converters is increasing day by day. Many different active power filters had been designed and developed, but for the sake of current harmonic compensation the shunt power filter is a feasible option to employ. And the series active power filters is a feasible solution to inject the voltage at a certain angle with the V_s to compensate the sag. The shunt compensation is done to inject current to maintain balance of the I_{source}. The greatest advantage of SMES is to regulate the P and Q independently. The PCS can be used as all the three compensators at a time (1). A power conditioner (2). An active power filter (3). A current harmonic eliminator.

1.4 Objective

The main objectives of this work are

i. Load compensation by using the PCS of SMES. The energy is said to be stored in the light loaded condition and the energy discharge should happen when there is heavy load on the system in order to save the system from losing its stability.
ii. Along with giving a back-up supply SMES is also regulated to make I_{source} in phase with L-N $V_{source}$to make it act as shunt filter. The P and Q delivered are said to be regulated independently.
iii. The $V_{capacitor}$, is made to be constant in order to exchange the energy from source to SMES and from SMES to load.

iv. To regulate the charge and discharge cycle of superconducting magnetic energy system so as to charge the coil to its rated value, which is possible by regulating the superconducting coil energy.

1.5 Thesis Composition

The thesis composition is described below

CHAPTER-1 consists of the intro to superconductivity and how this phenomenon used to in the power system. The main reason behind taking up this project had been described in the motivation. The research work that is carried out over the years were examined and produced in the literature survey. This chapter gives you the basic understanding of the project I have taken up by the motivation, literature survey and the main objectives.

CHAPTER-2 explains the superconductivity and gives an intro to SMES systems, the practical uses in the system to improve the stability, damping improvement etc. And also the practical uses explained in this chapter explains the applications used in machines, cables, t/f’s etc. are portrayed in this chapter.

CHAPTER-3 gives us view that how the SMES works, on what principle it operates. It explains how the energy balance is occurred. After analyzing the possible topologies to be implemented a final PCS implemented in this paper is explained.

CHAPTER-4 explains the control strategy used in the PCS of present model in order to regulate I_{sup}, V_{cap} and the E_{sc} by using 2 HB regulators and a PI regulator respectively.

CHAPTER-5 gives us the results obtained by the simulating the PCS designed. Not only results but also the conclusions of this whole results and the future work has been advised.

CHAPTER-2

1. **Introduction**
2. **Superconducting Magnetic Energy Storage System (SMES)**
3. **Practical Implementations**
4. **Applications**
5. **Conclusion**

Introduction

This chapter explains the superconductivity and gives an intro to SMES systems, the practical uses in the system to improve the stability, damping improvement etc. And also the practical uses explained in this chapter explains the applications used in machines, cables, t/f's etc. were portrayed.

2.1 Superconducting Magnetic Energy Storage System

The SMES model is a model which can store energy in the form of magnetic field. The magnetic field is created in the SC coil by the DC current flowing in it. As the energy stored by the current is circulating in nature, it can be drawn or stored instantaneously over the periods which may be ranging from milliseconds to several hours. An SMES unit in the fig 2.1 comprises of a large SC coil with a temperature that uses in cryogenic systems, which is maintained by cryostat that is consisting of the inert gases such as helium etc., or N_3liquid containers. A switch is used to bypass and to minimize the losses occurred by the energy particularly when the coil is at stand-by, which also serves in the other way like to bypass the SC coil current if any utilization tie is lost or to take the converter out from the service or to safeguard the SC coil whenever there is a malfunction in the cooling system [14]. Various factors were taken into consideration to get the best possible outcome as far as performance is concerned when designing the PCS of SMES with the minimum expense [15]. Temperature, energy capacity, coil design may also include these factors. An adjustment was made between every factor acknowledging the criterion of $\frac{E}{M}$ ratio, Lorentz law of forces to reduce the losses for stable, compatible and cost effective SMES model. The design of the coil can be solenoid or it can be a toroid. The most preferred configuration is the solenoid type from the fact that it is simple and possible with minimum cost [16]. L_{coil} and the I_{rating} of the SC coil will decide the maximum energy or the maximum power that is stored or to be supplied in the SC coil. The ratings of these criterions depends on the type of application of SMES. The temperature at which the SC device is operating is like a give-and-take between cost and the service requirements. The low temperature SC models are mainly used presently due to the economic related issues the HTS devices have been kept aside because the former's operational cost is very less and a high efficiency is possible with it.

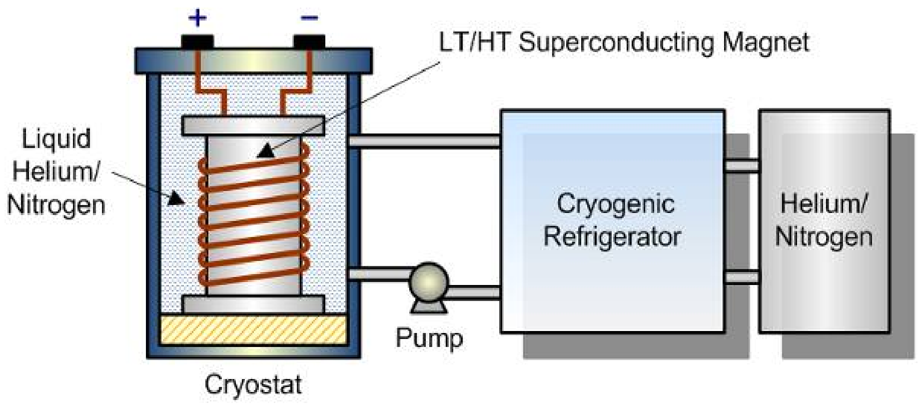

Fig 2.1: Basic Superconducting coil unit.

2.2 Practical Implementations

1. Induction heating
2. Fault current Limiter
3. SC power cables
4. SC Power Transformer
5. Rotating electrical machines with superconducting windings
6. Cryo-machines and electrical machines with massive superconductors
7. Super conducting magnetic energy storage system (SMES)
8. Magneto hydrodynamic generators (MHD)
9. Electro dynamic Levitation (e.g., high speed trains)
10. Particle accelerator (detector magnets, beam guidance magnets)
11. Synchrotron radiation sources

2.3 Applications

1. **Energy storage:**

   An SMES unit has a capability of storing the energy up to 4500Mwhr without compromising on the efficiency, which is as high as 95%, and very quick response as low as few milliseconds either it may be in the charging or discharging mode [17]-[25]. Because of this reason SMES is known to be ideal device for huge deflections in load and the corresponding demand fluctuations which also avoids large unit trips and takes the surplus energy. This ensures us to reduce the requirement of spinning reserves.

2. **Load compensation or levelling:**

   The load compensation can be done at a rate as quickly as a millisecond which gets charged in the off-load condition by taking the surplus energy from the source and gets discharged in the peak-load situations by giving the deficit energy, which ensures the generating units to operate without stability at the same output as before the load change by using SMES model [17].

3. **System stability:**

   The SMES model has the capacity to die the low frequency oscillations out and to maintain the system frequency intact, which is mainly caused due to the system transients [17] [27].

4. **Automatic Generation Control:**

   An SMES model can become the regulating function for the AGC model in order to fetch out a reduced ACE [17].

5. **Spinning reserve**

   Spinning reserve is defined as a full generating bulk kept on the bus-bar unloaded but used to respond to the sudden outages of either the generation or the transmission within minutes of outage. But the frequency sensitive SR can respond to the outages within 10 sec when the frequency drop is there in the power system. SMES is best suitable for this purpose and helps a great deal in maintaining the system stability and also minimizes the cost of SR's as SMES is the low cost replacement of spinning reserve [17], [18], [20].

6. **Reactive volt-ampere (VAR) control and power factor Correction**

   An SMES model will improve the stability and can also improve the power capacity of the transmission system [17].

7. **Black start capability**

   An SMES model can accommodate power to a generator in order to start even though there is no power from the grid. The significance of this method can be known when there is any fault occurred and grid is to be restored [17].

8. **Bulk energy management**

   An SMES model has the capability to store indefinite energy and based on the financial, practically lowering the overall unit cost of the electricity by making itself a charging and discharging point [17].

9. Transient voltage dip improvement

The voltage dip which is transient in nature lasts for 15-25 cycles intern causes severe stability problem. SMES had proved that it is a capable replacement for voltage compensation at the terminal end whenever there is a peak-load situation, which in turn increases the limitations of power transfer on the tr. System [21].

10. Dynamic voltage stability

The dynamic voltage instability is caused when there is a heavy loss of generation or when the fully loaded tr. line and can also be caused due to the deficient dynamic Q to back the voltages. SMES has proved itself to be a capable device to solve the dynamic voltage instability problem by providing P and Q at a time by backing up to the generation loss or a loaded tr. Line [20], [21].

11. Tie line control

It is necessary that the P_{actual}net should be closely equal to $P_{scheduled}$, if the power is said to be supplied in between the two control areas. It is not lucky to say that if the generators beefed up in one area then in the other area they will be down to transfer power, the load on the system might become a reason for error in the P_{actual} delivered. The ACE might become a reason for the ineffective use of P_{gen}. SMES has been developed and tested with needed regulators in order to inject P and Q to basically make the error zero and to ensure the efficiency is maintained and all the power demand is met [21].

12. Under frequency load shedding reduction

If there is any loss of chief power source like a major generating station or a fully loaded transmission line the frequency drops drastically till there is a balance occurred between the source and load. SMES model had been developed and tested to become a capable model to minimize low frequency problems as it lessens the difference between load and supply [21].

13. Circuit breaker reclosing

After the fault is cleared, CB's try to reclose and try to take the system to the operational state or the tr. line again into service. This is done very commonly when the δ difference is within the limits. Anyways, relays also plays a major crucial in preventing the CB's from reclosing when the δ difference is too big. SMES can become an affordable device to minimize the δ by taking a fraction of power which is generally transmitted by the tr. line and makes the CB's to reclose without any hurdle. Helps the system to restore to the fullest at the time of outages on crucial tr. lines [21].

14. Power quality improvement

SMES plays a very effective role in smoothening out the disturbances on our system which might cause problem to the acute consumer loads. If the ephemeral problems such as lightning strikes, there is a possibility of losing the power if the tr. line trips, or can cause a voltage dip. SMES plays a very crucial role as far response time is concerned to inject P in less than 0.4 milliseconds helping consumers without the outage or the penalties [21].

15. Backup power supply

The SMES is utilized as a back-up supply if and when there a sudden outage main power supply with the excellent energy storing capability. It had been proved by the studies that SMES model is the very effective model to be used as a back-up to supply P and Q independently for indefinite amount of time [20], [21].

16. Sub synchronous resonance damping

The SSR is experienced when the generators in combination with the tr. lines have the heavy quantities of series capacitors, which might cause a severe damage to the generator. SMES plays a very crucial role in lessening the SSR by allowing the greater levels of series compensation [21], [31].

17. Electromagnetic launcher

This launcher needs high frequency power pulse source had been designed and tested as a rail gun for military utilities. The projectiles with a speed of greater than 2000 m/s, surpassing the orthodox potentials is possible with the rail gun. Because of its very high power capability, SMES will be a feasible device to be used as a launcher [38].

18. Wind generator stabilization

The generators used in the wind plant will have transient related limitations at the time disturbances caused in the network. The SMES model with the bidirectional IGBT's or GTO's is apt in regulating both P and Q independently and at the very same time. That is the reason why it is a reliable device to depend on to balance the wind generating plant without any stability issues [34], [36].

19. Minimization of power and voltage fluctuations of wind generator

Because of the unpredictable changes in the wind speed, the P_{out}, and the V_{out} will also fluctuate accordingly, that are severe and pose drastic effect on the system. For e.g. a lamp flickering due to the wind surrounding it and it's not so good accuracy in the timing devices. The fluctuations in the power and voltage of wind plant can be minimized as the SMES model designed is very efficient in handling the P and Q independently and concurrently [32], [39].

2.4 Conclusion

This chapter gave all the practical implementations and the wide range of applications in which the SMES can be used, like harmonic compensation, load compensation, load frequency shedding, tie line control etc.

CHAPTER-3

1. **Introduction**
2. **Working Principle**
3. **Structure of the Model**
4. **Conclusion**

Introduction

This chapter gives us view that how the SMES works, on what principle it operates. It explains how the energy balance is occurred. After analyzing the possible topologies to be implemented a final PCS implemented in this paper is explained.

3.1 Principle of Operation

The system runs on the principle of load-source-SMES coil energy balance [11]. The supply current depends on two more currents, Load current and compensating current.

$$I_{sup} + I_{comp} = I_{load} \qquad (1)$$

Where I_{sup} = supply Current

I_{load} = Load Current

I_{comp} = Inverter Current

But the compensating current I_{comp} is the function of the duty cycle of the bi-directional chopper and the M.I of the VSC and the SC coil current I_{sc}.

$$I_{comp} = F(I_{sc}, D, M) \qquad (2)$$

Where I_{sc} = SMES coil current

D = Duty cycle of the chopper

M = modulation Index of VSC.

While load compensation situation, the surplus energy from the supply after supplying the load is responsible for the charging of the SC coil. The energy is said to be stored in this condition. In this situation the $P_{supply} > P_{load}$, and the $P_{SMES} = P_{supply} - P_{load}$. Generally occurs in the light loaded condition and also avoids Ferranti effect.

Whenever there is a heavy load demand or at the system is at peak-loaded condition the deficient energy in the load is supplied by the SMES and now the coil will be discharging the stored energy. Load balance is done in this way. However, the capacitor voltage will remain constant though out but fluctuates about the reference value. Here, $P_{supply} < P_{load}$.

The conduct of the system with a voltage tolerance on $V_{capacitor}$ and the current tolance on

I_{supply} was carried out. The voltage across the capacitor when the SC coil is getting charged will be given by

$$\mathrm{V_{cap}}(\mathrm{t} + t') = \mathrm{V_{cap}}(\mathrm{t}) - \left(\frac{\mathrm{I_{sc}(t)}}{\mathrm{C}}\right)t' \tag{3}$$

Where V_{cap} the dc-link voltage (Volts), C is is the magnitude of capacitance (Farad), and I_{sc} is the $I_{inductor}$, that rises to a value of

$$I_{sc}(t + t') = I_{sc}(t) + \left(\frac{V_{cap}(t)}{L}\right)t' \tag{4}$$

If the SC coil is discharging then the voltage across the DC-link builds up to

$$V_{cap}(t + t') = V_{cap}(t) + \left(\frac{I_{sc}(t)}{C}\right)t' \tag{5}$$

And the $I_{inductor}$ would reduce to a value of

$$I_{sc}(t + t') = I_{sc}(t) - \left(\frac{V_{cap}(t)}{L}\right)t' \tag{6}$$

Correspondingly, coming to the inverter side, to modify the optimized value of $V_{capacitor}$ the hysteresis regulator is used to control the value of source current accordingly. During the current rise i.e. I_{supply} rising towards the upper limit

$$I_{sup}(t + t') = I_{sup}(t) + \left(\frac{V_{sup} - V_{cap}(t)}{L_{sup}}\right)t' \tag{7}$$

The $V_{capacitor}$ will rose to

$$V_{cap}(t + t') = V_{cap}(t) + \left(\frac{I_{sup}(t)}{C}\right)t' \tag{8}$$

Correspondingly, if the upper band is acquired, the I_{sup} starts decreasing towards the lower band; the value then implies

$$I_{sup}(t + t') = I_{sup}(t) + \left(\frac{V_{sup} - V_{cap}(t)}{L_{sup}}\right)t' \tag{9}$$

And dc-link voltage will be reduced to

$$V_{cap}(t + t') = V_{cap}(t) - \left(\frac{I_{sup}(t)}{c}\right)t' \tag{10}$$

The power flow at the time of charging and the discharging periods is shown in the fig (3.1). Now it can also control the maximum load demand. The coil is said to be charged when the load power is less than the source power and the coil discharges when the load power is greater than the supply power at the load compensation basically. Energy balance is met with the help of SMES and the capacitor voltage is kept constant throughout the charge-discharge cycle.

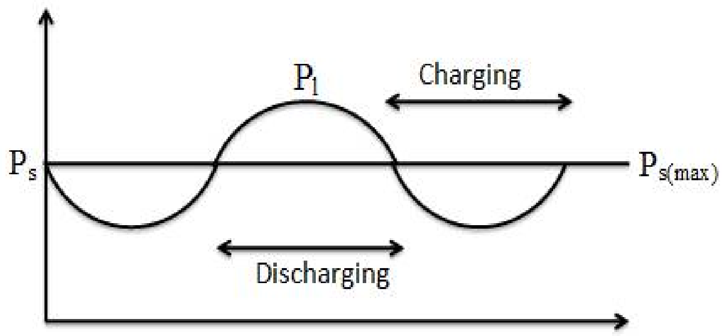

Figure 3.1: Functioning of PCS under Load compensation.

3.2 Structure of the Model

The topology is pictorially represented in the fig (3.2.1). It basically, comprises of a source and a pulsating load, which is a 3 phase diode rectifier, and the PCS is connected in between comprises of a bidirectional VSC, a DC-DC bidirectional chopper and a superconducting coil. But there is one more PCS based on CSC which don't need chopper and a dc-link in order to connect it to the load.

3.2.1.1 VSC Built PCS

Fig 3.2.1.1 shows the pictorial representation of the VSC built PCS [47], [56], [57]. The VSC based PCS consists of a 6 pulse hysteresis band bi-directional VSC with the IGBT switches with an anti-parallel diodes to make it feasible for both charging and discharging, a bi-directional DC/DC converter with simple IGBT's (no diode in anti-parallel) and diodes a SC coil and a dc-link which is used to cascade or decouple both VSC and chopper ensuring the voltage across it to be constant always. Actually this PCS is used as an interface to connect the SC coil with the source. In order generate pulses for the VSC the reference and the actual compensating currents were compared in each phase and the error produced is passed through a relay, which sets a band, and the pulses generated were given to the IGBT switches accordingly. The VSC acts as an Ac-Dc converter in charging mode and as an inverter in the discharging mode. The output of the converter is always kept constant by the DC –link throughout in the charging period and even in discharging period the voltage across the dc-link is constant [34], [41].

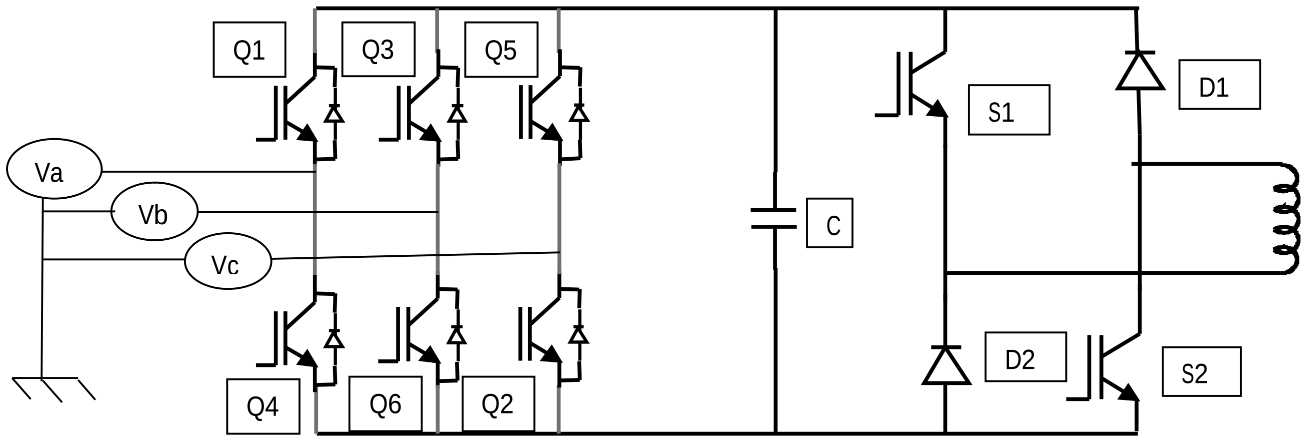

Figure 3.2: Voltage Source Converter built Power Conditioning System.

A 2 quad DC-DC converter used in this PCS consists of simple IGBT's and simple diodes. That means the IGBT's don't have anti-parallel diodes across them. In the charging mode, the SC coil will be charged through the two IGBT's and during the discharging mode, the SC coil is discharged through the diodes. The pulses are generated in such a way that they will be positive (switch on state) while charging and will be negative (switches in off state) while discharging. Therefore, in this chopper helps in regulating the charge-discharge cycle. The duty cycle of the chopper determines the charging and discharging modes, which is known by the V_{avg} across the coil. Finally, the pulses are generated by comparing the V_{ref} of the dc-link capacitor, which depends on the peak line to neutral supply voltage, and the V_{actual}. The error given to relay to generate the pulses accordingly [41].

3.2.1.2 CSC Built PCS

The model of CSC based PCS is pictorially represented in the fig (3.2.1.2). The AC supply and the SC coil were being interfaced by a CSC. To improve the speed of the energy transfer the DC capacitor banks are used to act as a buffer to the source inductance in the process of commutating the L_{line}. In addition to that the capacitors also acts as a filters in order to eliminate the higher order fluctuations of AC I_{line}. The greatest plus using CSC based PCS is that the current in the SC coil is modulated and the pulses are generated accordingly to the switches. As the CSC based PCS is a current source by seeing the inner character of the coil, as it stores and discharges the energy with the help of current in the coil. That ensures the PCS to transfer the P and Q very quickly if and when there is a need and independently [45].

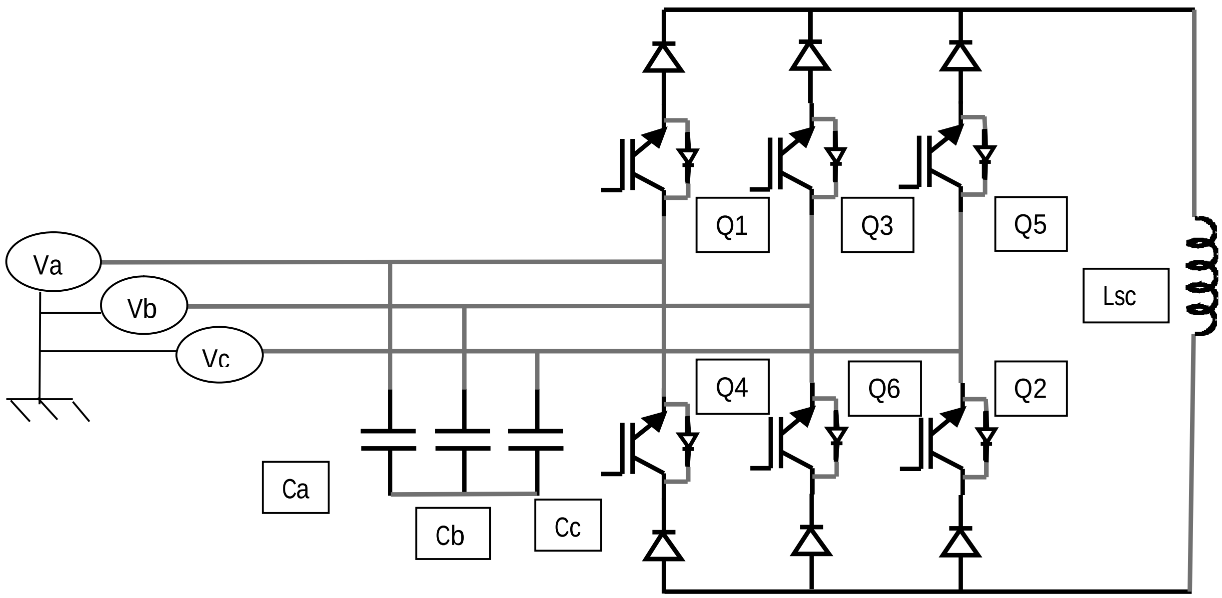

Figure 3.3: Current Source Converter built PCS

In case of twelve pulse CSC based PCS, in order to lessen the distortions of the I_{source}, the optimized PWM technique is used to reduce fifth, seventh, eleventh and thirteenth harmonics or can also be eliminate them completely to zero if the M.I is made to be from .2 to 1 [46]. The twelve-pulse CSC has a little less voltage ripple when compared with the six pulse CSC to make a decrease in the losses of the SC coil.

But the basic structure of CSC will not be similar to VSC unlike it won't be having a DC-DC chopper in between to interface the SC coil and the VSC and therefore there is no need of a dc link capacitor as the main purpose of DC-link is to maintain the constant voltage across the dc-dc chopper. And the switches of CSC consists of IGBT's with anti-parallel diodes and the also a single diode whose cathode terminal is connected to the collector of each IGBT. The bi-directional operation is even possible with this kind of converter with even better way as far as speed of the operation is concerned. The

The similarities and differences or the advantages and disadvantages were produced below in the [table 3.2.1].

Criteria	VSC based	CSC based
P and Q Power Control Ability	The independent regulation is possible to supply P and Q powers with a quick access. The rated Q is achieved whenever there is very low coil current or no I.	Provides independent R powers instantaneously acts as a bridge between superconducting coil and load to transfer the energy and it can also supply high levels of Q but dependent on the coil current.
Control topology	Relatively complicated to CSC based SMES and contains a VSC, a dc/dc chopper, a dc-link to decouple both VSC and dc-dc chopper and a superconducting coil.	CSC based a little simple in design relative to VSC based PCS. It comprise of only a single converter and a coil. It can be used in high power circuit to be paralleled in the multiple stages.
THD	Less	Less
V_{Ripple} in coil	Ripple in the voltage across the coil when used a VSC based PCS.	The ripple in CSC based PCS is a little when used a 12-pulse one. The losses in the coil currents are also reduced with this type.

Table 3.2.1: Comparison between VSC and CSC built PCS.

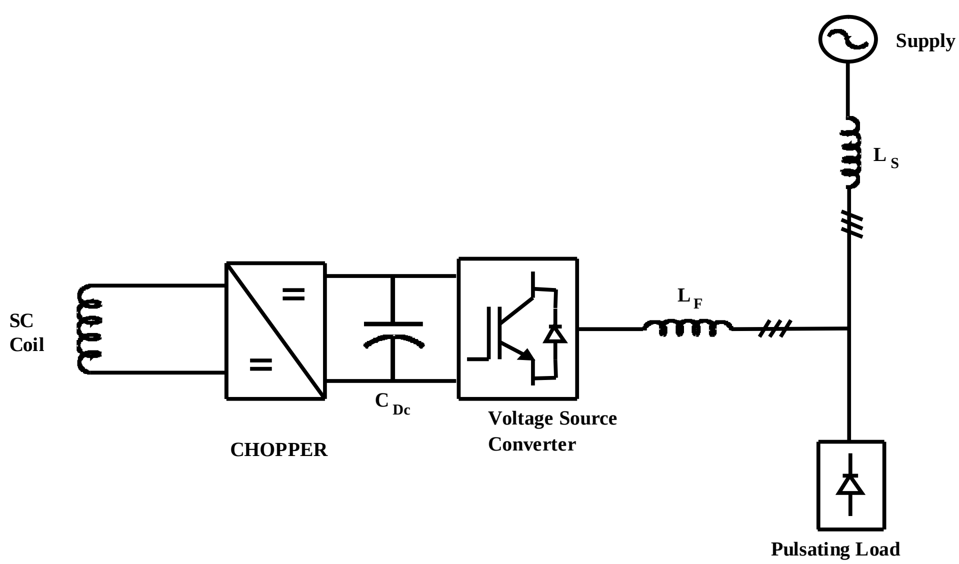

Figure 3.4: Designed System Structure

The topology shows you the VSC based PCS, which comprises of a VSC, a chopper, a dc-link and a SC coil. Chopper takes care of charging and discharging of SMES. It consists of the simple IGBT's as explained earlier. They will be in the on state when charging and will be in the off state when discharging and it occurs through the diodes. The current direction won't change even when it is discharging. But in the stand-by mode the I_{sc}will pass through one IGBT and one diode to keep the current at the constant position. The switching sequence is regulated to get a voltage of the dc-link fluctuating about a reference value. The ac-dc and dc-ac operations done by VSC at the time of charging and discharging respectively is taken care by the VSC.

3.2.2 DC/DC Chopper

The most important function of the dc-dc converter is to regulate the charging and discharging cycle of SMES, which means the energy balance. While charging, it acts as an interface between capacitor and the SC coil and the output of the chopper which is fluctuating between two limits will charge the SC coil making power flow from capacitor to SC coil. While discharging, it will connect the capacitor with reverse polarity to the original one, in order to ensure the power flow is reversed. The rate is depended on the mag of V_{sc}. The in or out depends upon the mag of V_{sc}. The comprehensive representation of the 2-Quad chopper is shown in fig 3.2.2.

As drawn in the fig (3.2.2), when the 2 switches are said to be triggered at a time and the diodes get automatically RB. The current flow to the SC coil from the supply though VSC, dc-link, chopper and the positive voltage is applied to the SC coil. So the coil gets charged in this way. The diodes automatically gets turned on when the 2 switches got a negative trigger to turn off and the current flows from SC coil to load through chopper, dc-link and the VSC. The negative V_{sc} is applied on the SC coil to ensure the discharging. The δ f the chopper decides the charging and discharging of SMES and the V_{sc} is also controlled using δ. If the δ is equal to .5, then the V_{scavg}, and the current through the PCS of SMES is both 0 and the device is said to be in idle state. The power transferred is 0 in a whole cycle. When the $\delta > 0.5$, then the voltage V_{scavg} is positive and we say the SC coil will be charging and the current obviously flows from supply to SC coil through VSC based PCS. The extra energy from the source is transferred to the coil. If the $\delta < 0.5$, then the coil is said to be in the discharging state as the $V_{scavg}$is negative and the deficit energy needed by the load is supplied by the stored energy in the coil. Finally, charge discharge cycle depends upon the duty cycle δ of the chopper.

The changes made in the working of dc-dc converter can minimize the ripple content in the current waveform in the following manner. Even when the model not used after the charging of the SC coil it can be used for the future purpose. It is possible by triggering any one of the switches to on position and making the coil current to flow continuously. When the switch S1 is on and the current path will be from coil, diode D1, S1 and back to coil and the $V_{scavg}$is zero because of the short circuit. At this time, the SC coil and the capacitor are not in connection as the S2 and D2 will be in off position. And the total capacity of energy in the coil is almost constant as there is no discharging path or a charging path. If at all we want the pcs to be charged then turn on the S2 and then then the coil starts charging. To make the SMES to discharge both the switches are made to be in the on position.

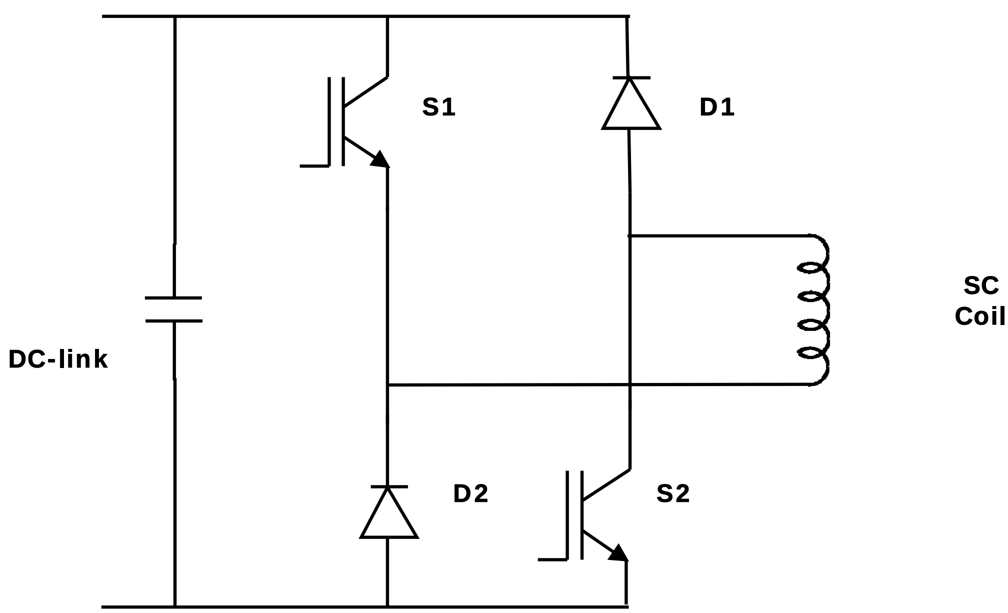

Figure 3.2.2: Two quadrant voltage bidirectional DC/DC converter

3.4 Conclusion

This chapter explained the principle of operation of the PCS of SMES model. It also explained the various block of the PCS like VSC, DC/DC chopper and also their bi-directional nature has been explained.

CHAPTER-4

1. **Introduction**
2. **Hysteresis Band regulator**
3. **Regulation scheme**
4. **Conclusion**

Introduction

This chapter explains the control strategy used in the PCS of present model in order to regulate I_{sup}, V_{cap} and the E_{sc} by using 2 HB regulators and a PI regulator respectively.

4.1 Hysteresis Band Regulator

Many regulating methods had been proposed and even used practically to regulate the current or the energy which may be a linearized or non-linearized control technique. Various PWM approaches are mainly made to use to relate F_{low} ref wave with the F_{high} carrier wave. But the Hysteresis regulator has come to light as a very useful and simple NL regulation technique to be achieved in low cost and can also designed easily. The other assets are

(i) The assurance of stability at any situation.

(ii) The responding time is as quick as a millisecond.

(iii) There improved and better accuracy relative to other strategies.

(iv) Can be possible to design with very little expenses.

In spite of these assets the HC has, it displays many liabilities. The very major one from the pack is that it generates triggering pulses of variable f. This causes some serious problems in developing the filter and produces resonances which are undesirable in the source side and also causes noises. The other important liability of the HC is that its conduct will have a reverse effect among the phase currents, majorly occurred in the systems having an insulated grounding system [65]. Many changes to the existing had been made and even designed in that manner to get rid of these liabilities [61] to [63]. Firstly, the phase current decoupling had been fixed by the researchers [61]. Secondly, a steady modulation f had been obtained by using a HC which is adaptive in nature. This possible by giving a varied width accordingly [61], [64].

The fig gives you the most commonly used regulation technique, which is done to regulate the I_{sup}. There is band about the I^*_{sup}, where the ref current is represented as I^*_{sup} and the actual is represented as I_{sup}. The HB current regulator gives us the sequence of the switches of P filter [67]. The technique is represented as:

If $I_{sup} < (I^*_{sup} - HB)$ the S1 will become OFF and S4 will become ON.

If $I_{sup} > (I^*_{sup} + HB)$ the S1 will become ON and S4 will become OFF in case of leg 1 in the VSC. That will be similar in case of remaining two legs.

The $f_{switching}$ of the HB CCM explains that how quickly the I jumps from lower point of the HB to upper band and from upper point of the HB to lower point of the HB [66].

The $f_{switching}$ is calculated by the pace at which the actual I_{sup} is changing, which is why the $f_{switching}$ is not same at points of time and changes with the I_{sup}. However, the $f_{switching}$ is not the only variable which decides the rate at which the I_{sup} changes but also the V_{cap}, L_{line} helps in determining the rate. But the latter plays a major role to the former.

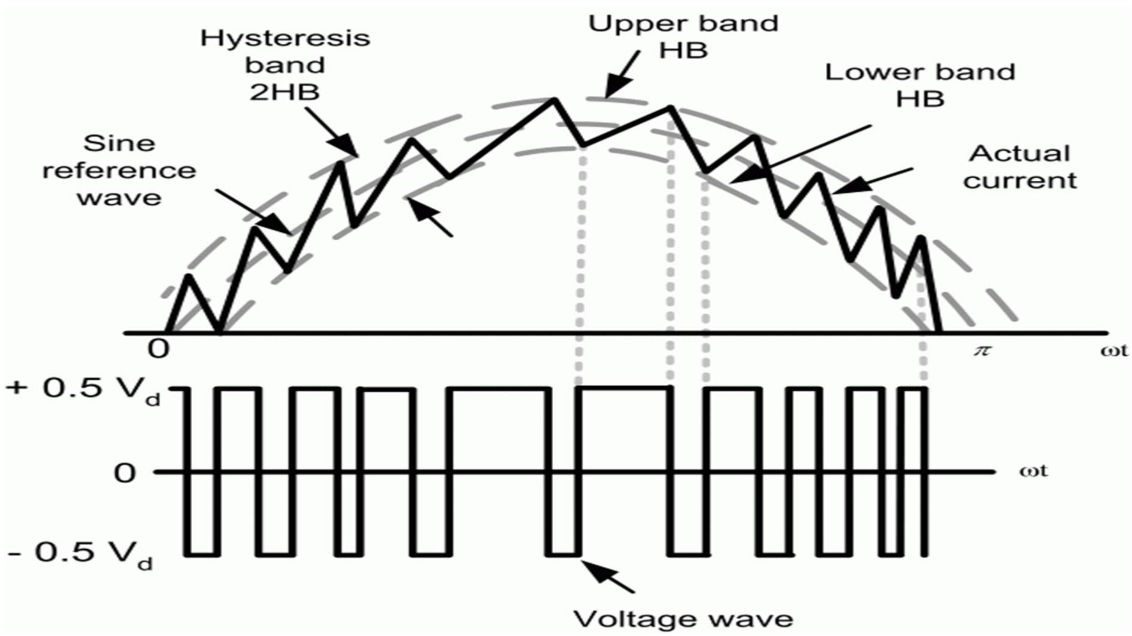

Figure 4.1: Operation of Hysteresis Band Controller

Here, the VSC and chopper is regulated by simple HB regulator. A non-linearized regulator one and can also be used with better performance oriented results. The difference b/w act and ref I_{sup} gives you the triggering pulses for the AC-DC converter while seeing from the source side. If the difference signal reaches the upper point then the top switch gets on and the bottom switch gets on when the error value reaches the lower point.

In case of chopper the error of the V_{act} and V_{ref} is given to a relay where the band is being set in order not to cross the band limit and the pulses are produced accordingly to the two IGBT's.

4.3 Regulation scheme

In this paper, I used PCS of SMES for compensating purpose and to almost nullify the load harmonics. As it is current charging device, it is used as a current supply to the deficit load and can also provide P and Q independently and at the same time. The surplus source energy decides the charging rate and the deficit load decides the discharging rate and therefore the I_{sup} and the I_{load} decides the charging and discharging respectively. The Q demand is met by the model as the I_{sup} maintained in $\emptyset$ with the V_{sup}. But the P supplied will depend on the strength of surplus energy and load utilities

While load compensation situation, the surplus energy from the supply after supplying the load is responsible for the charging of the SC coil. The energy is said to be stored in this condition. In this situation the $P_{supply} > P_{load}$ and the $P_{SMES} = P_{supply} - P_{load}$. Generally occurs in the light loaded condition and also avoids Ferranti effect.

Whenever there is a heavy load demand or at the system is at peak-loaded condition the deficient energy in the load is supplied by the SMES and now the coil will be discharging the stored energy. Load balance is done in this way. However, the capacitor voltage will remain constant though out but fluctuates about the reference value. Here, $P_{supply} < P_{load}$.

But if at all the $P_{supply} = P_{load}$, then the power to SMES is zero and this mode is called no charging – no discharging mode. Here, the SMES model will be in the idle state.

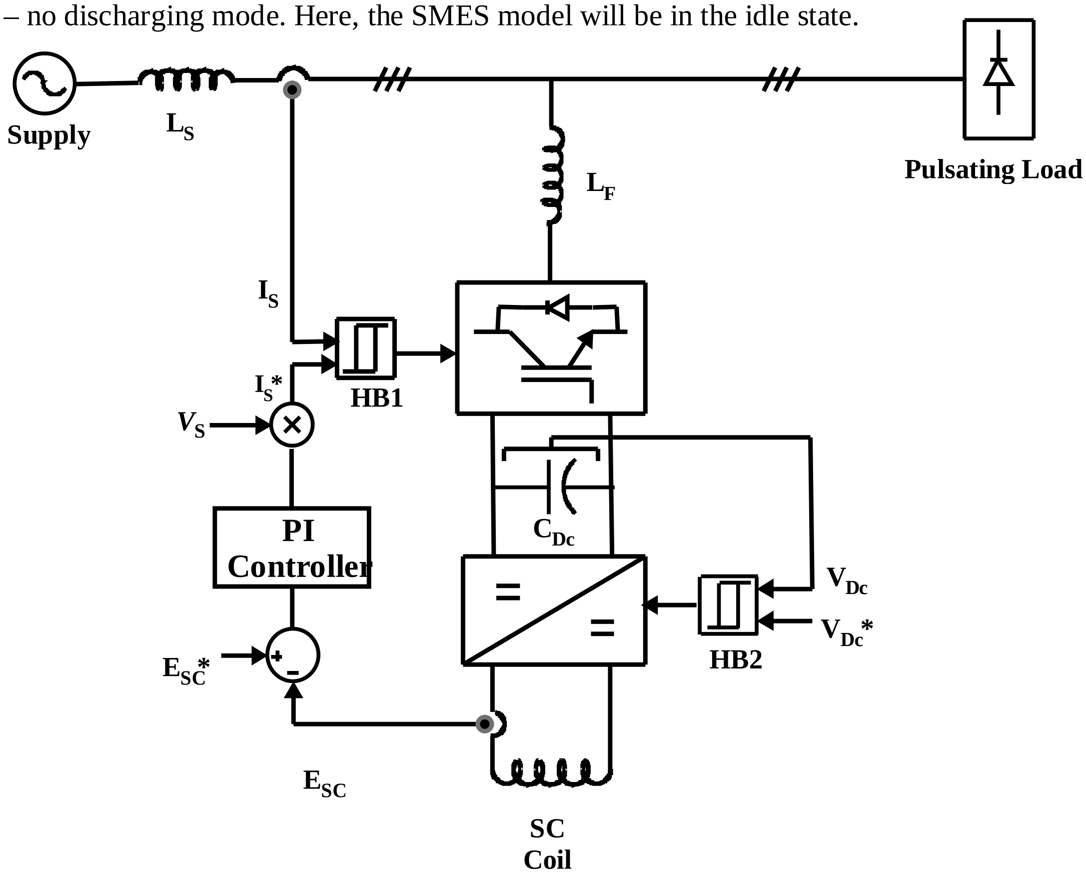

Figure 4.3.1: Proposed Regulation scheme

In order to regulate the energy of the SMES a PI regulator is utilized in this paper. The control strategy of SMES comprises of a PI regulator and 2 HB regulators. To produce pulses for the VSC the PI regulator and a HB regulator is made to use. And to produce pulses for a chopper just a HB regulator is used. Firstly, to generate pulses for the VSC, the error energy when the actual and ref energies are compared is said to be passed through a PI regulator and the out of that is passed through a saturation block in order to generateI_{max}. Now with this I_{max} the ref I_{sup} is generated by dividing the magnitude of I_{max} with V_{speak} and multiplying with the source voltage. Now, the output of the whole is $I_{sup}^{*}$of the phases ABC. The ref signal is made to compare with the actual load current to get theI_{comp}^{*}. The I_{comp}^{*} and $I_{comp}$is compared and the error generated is made to pass through a relay to generate pulses to the VSC. Here, the reference energy depends on the maximum current through the SC coil. $E_{SC}^{*} = \frac{1}{2} L I_{scmax}{}^{2}$. The figure shown below is the model to generate pulses [10].

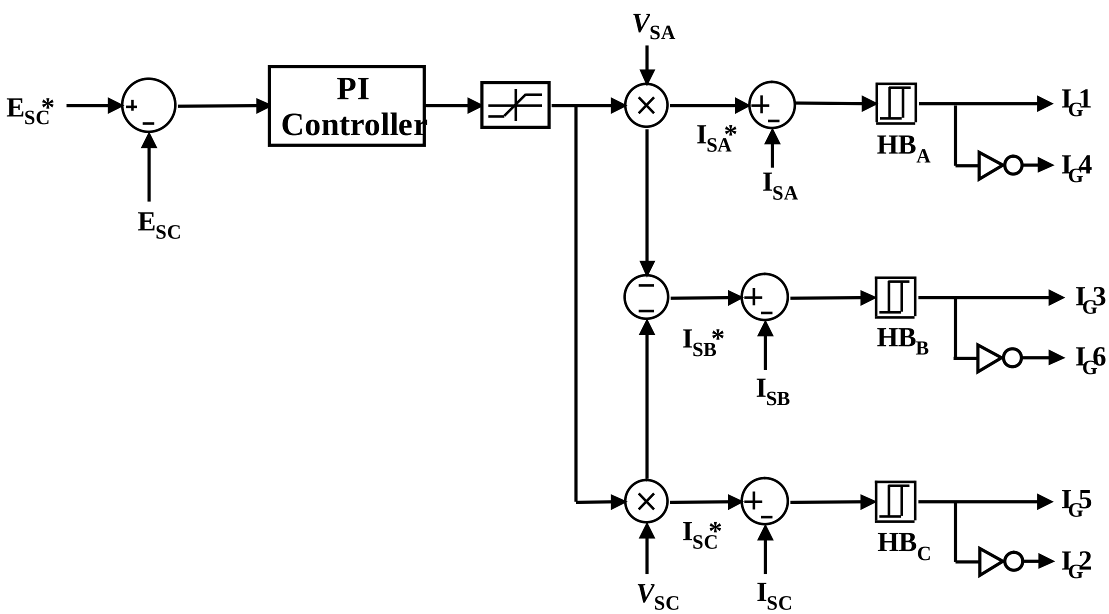

Figure 4.3.3: Pulses Production to VSC.

To generate pulses for the chopper, the $V_{cap}^{*}$and the $V_{cap}$are to be compared and made to pass through a relay where a band is set to bind the error voltage and the pulses are generated accordingly. Here, the V_{cap}^{*} depends on the peak line to neutral voltage of the supply.

4.4 Conclusion

This chapter explained us all the control strategies used in the PCS like hysteresis controller and PI controller. It also explained the switching sequence generation of VSC and the chopper by using two HB regulators and one PI controller.

CHAPTER-V

1. **Simulated Results**
2. **Conclusion and Discussion**
3. **Future Scope**
4. **References**

5.1 Simulated Results:

The designed PS is obtained by MATLAB/Simulink method. The conduct of all three modes have been detailed. A $3-\emptyset$ Y connected V_{sup} with the ratings of 400V RMS has been used as the supply of power. And a $3-\emptyset$ $diode\ rectifier$ has been used as a pulsating load. A SC coil (an inductor in theoretical case) of value 1H is used with a maximum current of 150A, and corresponding energy maximum will obviously depends on the magnitude of inductance and the I_{scmax}. Firstly, the coil charges up to 0.45 sec as the $I_{sup} > I_{load}$, since they are 50A and 11 A respectively. It is set to saturate after it reaches the $I_{scmax} = 150A$. At this point of time the stand-by mode starts from and the coil current used to oscillate about the I_{scmax} for a certain time and settles down to a value of 150A. At 0.695 sec the coil comes to steady state and is ready to discharge if any load change occurs. At 0.7 sec the load is increased to 100A, which is far higher than the rated I_{sup}. The increased load demand is supplied by the SC coil as it starts discharging at that instant. So, it is proved that the model can supply P and Q quickly both at a time which is required by the increased load and even compensated the harmonics in the load. The phase difference between V_{sup} and I_{sup} is obtained zero in all the 3 modes of operation of model and can be implicated as an active power filter. The THD's of I_{sup} in charging and discharging modes is within the IEEE standards of 5%. The waveform results of V_{supply}, I_{supply}, I_{load}, I_{comp}, $V_{capacitor}$, I_{sc} and the THD's of all the three modes were represented individually. PI controller is used to regulate the energy of the SMES.

The desired responses are shown in [fig: 5.1.1-5.1.7].

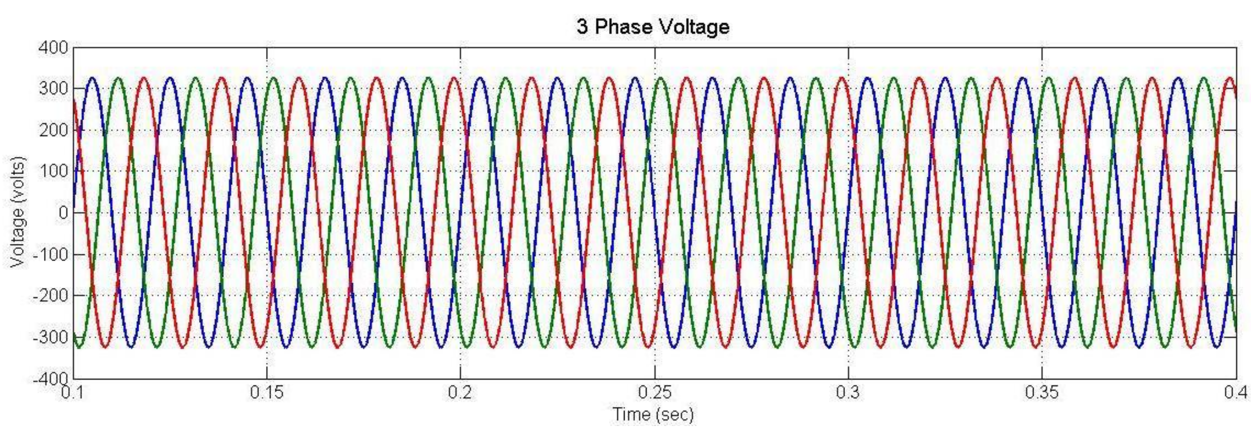

Figure 5.1: Plot of V_{supply} $(volts)$ vs time (sec) with PI regulator.

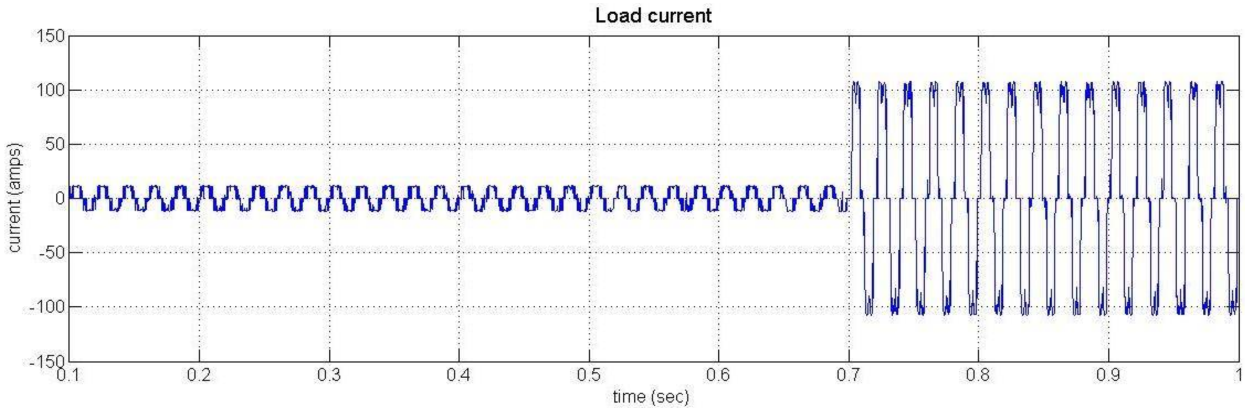

Figure 5.2: Plot of $I_{load}(amps) vs\ time(sec)$, with an increase in load at 0.7 sec from 11A to 100A.

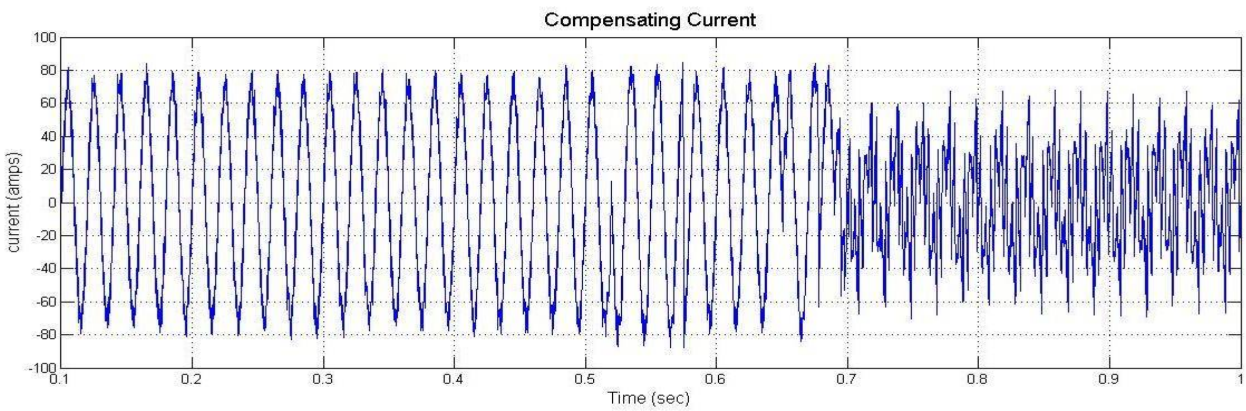

Figure 5.3: Plot of $I_{comp}(amps) vs\ time\ (sec)$, with an increase in load at 0.7 sec.

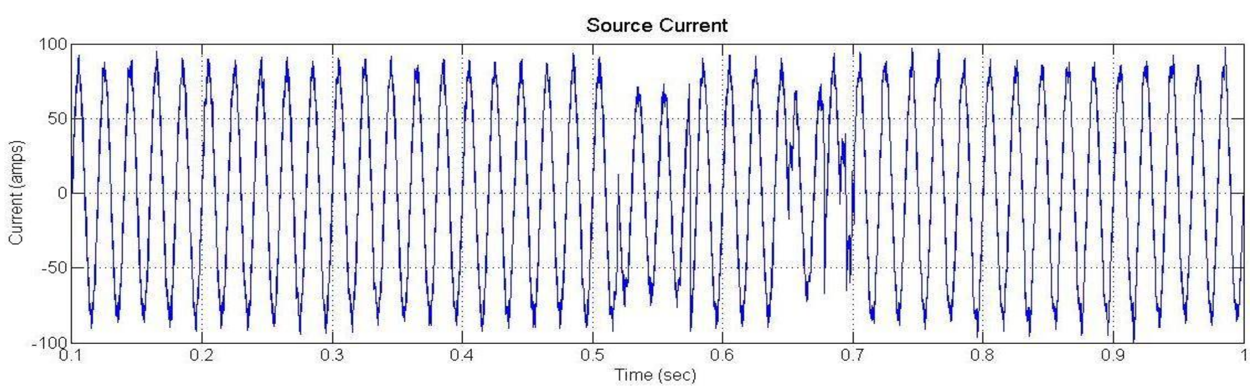

Figure 5.4: Plot of $A\ phase\ I_{supply}(amps) vs\ time\ (sec)$.

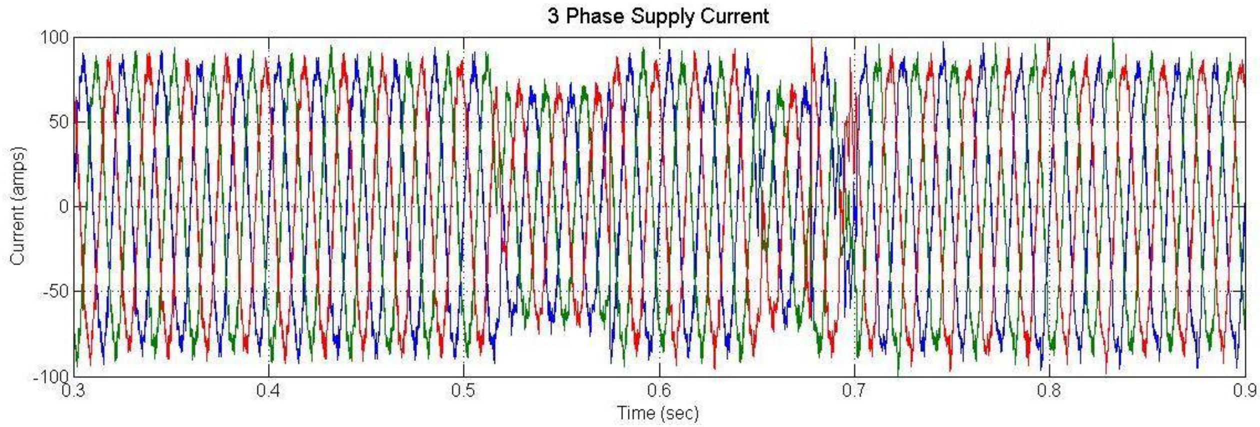

Figure 5.5: Plot of $3-\emptyset\ I_{supply} currents\ (amps) vs\ time\ (sec)$ using a PI regulator.

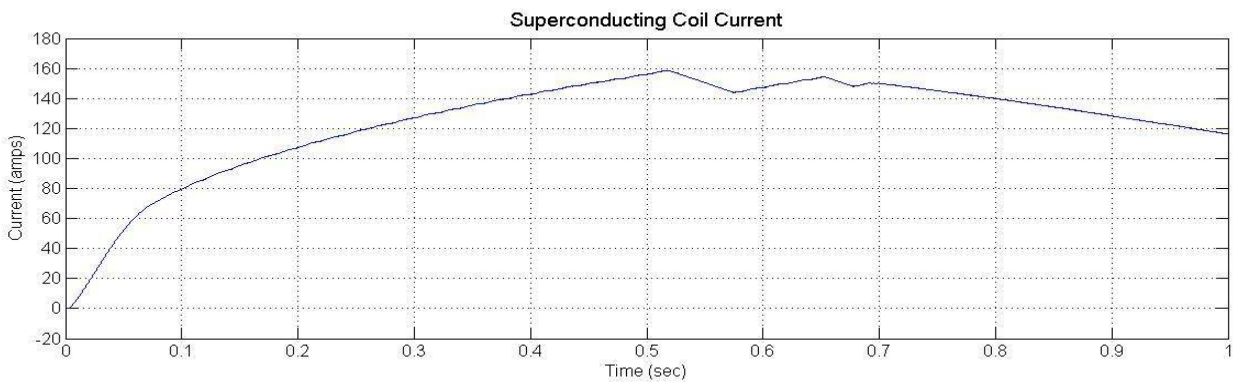

Figure 5.6: Waveform of I_{SC} w.r.t time (sec). Rises to the saturation point of 150A at 0.45 sec and oscillates about the maximum up to 0.695 sec and starts drooping after the increase in load.

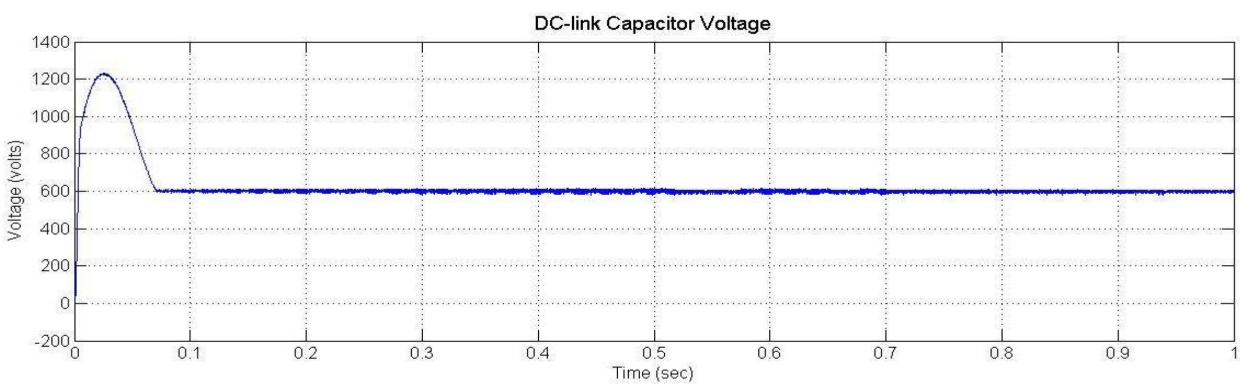

Figure 5.7: Plot of $V_{capacitor} (volts) vs\ time\ (sec)$using a H.B controller, where the voltage across is maintained constant but oscillate about the S.S value of 600V.

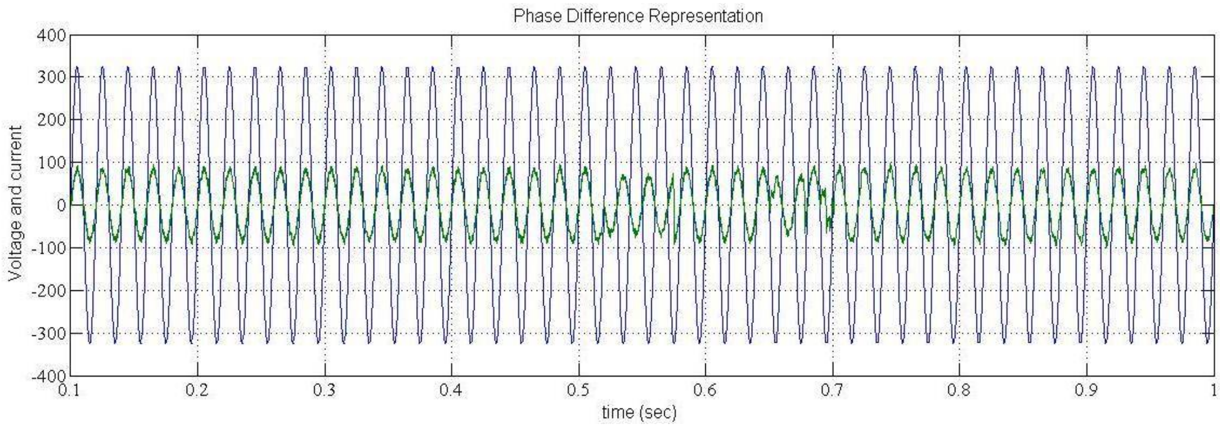

Figure 5.8: The Phase difference between $V_{supply}\, and\ I_{supply}$ of phase A in all the 3 modes.

The waveform results of I_{sup} using a PI regulator are satisfactory in charging and discharging modes as the THD of these modes are within the limits as per IEEE standards (which is < 5%). But the in the stand-by mode it is little bit more than the actual accepted standards. Through the FFT analysis the harmonic distortion is obtained and presented below in [fig: 5.9-5.11].

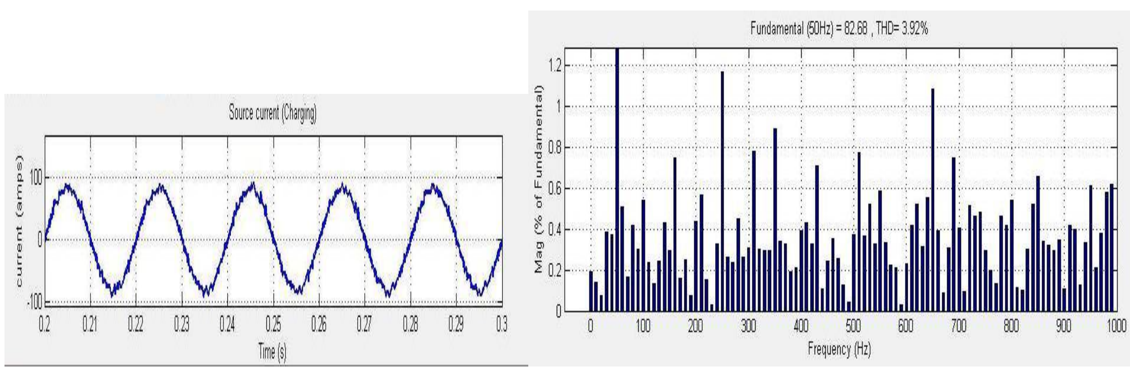

Figure 5.9: THD of I_{sup} while charging the SC coil.

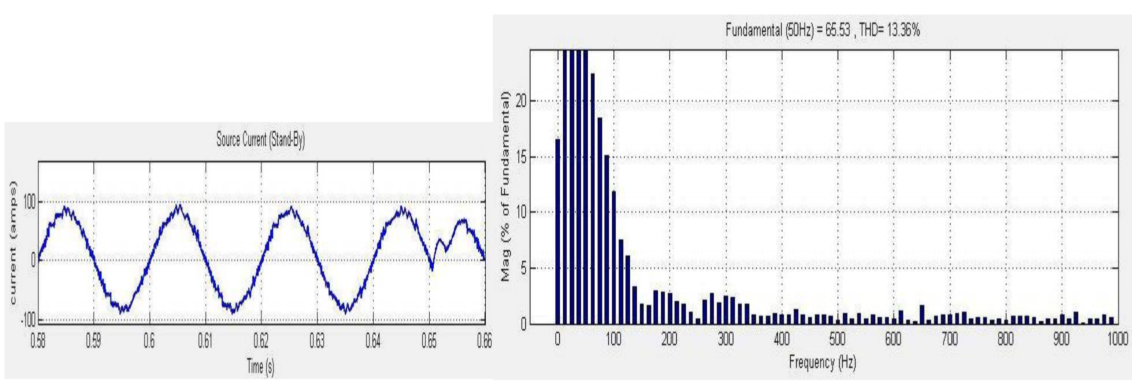

Figure 5.10: THD of I_{sup} in stand-by mode of PCS of SMES

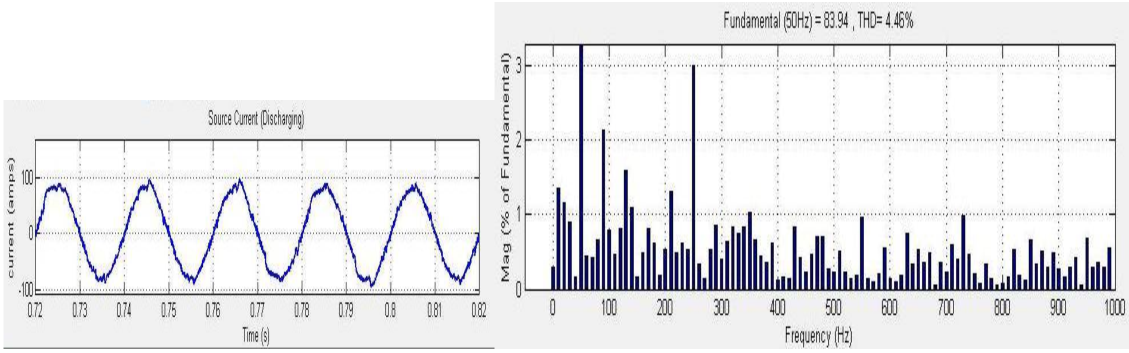

Figure 5.11: THD of I_{sup} while discharging of SC coil.

Source Current when	THD
Charging	3.92
Stand-by	13.36
Discharging	4.46

Table 5.1: The THD of all three modes (charging, stand-by and discharging).

5.2 Conclusion and Discussion

The results gives us a view that whatever the mode it had been in or whatever may be the load situation the I_{sup} is maintained in sinusoidal form only. The THD's of all the three modes is below 5% which is accepted as per standards. In the charging condition it is getting a little less THD to the discharging condition as the former has 3.92% and the latter has 4.46% which are well below the standards. But in the stand-by condition it exceeded the acceptable limit as its HD is 13.36 which is highly not acceptable. But the basic objective, the load compensation by supplying both the P and Q at a time, has been met and will be very effective in practical purposes. Even it can be used for harmonic elimination purpose at the time of storing the energy or discharging the energy but not when the SMES is idle.

5.3 Future Scope

With FLC and the fuzzy optimization techniques the THD can be minimized in the standby situation. The HB regulator is replaced with the adaptive HB technique, as the former has the frequency which is variable. But the latter technique is a technique that can rectify the problem of frequency change by varying the hysteresis band to make the f constant at every situation accordingly. Further modifications can be made to the chopper to lessen the harmonics by a using PWM regulator.

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